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Chemical Abundances and Their Relation with PN Morphological Features

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Abstract. Results appeared since the last APN meeting on the relation between abundances and PNe morphological features are reviewed here. Statistical analyses of round, elliptical, and bipolar PNe clearly separate the latter group as having larger He and N/O abundances. Studies of individual PNe, including the UV and IR domains, allow a detailed comparison with evolutionary models for the AGB phase; the abundances of most important elements can be matched but an 'age-metallicity' problem for the progenitors of He-rich PNe is implied. Halo abundances do not show strong chemical differences with respect to the PN rims, but the halos' faintness requires deeper data to confirm it. Data on the chemistry of microstructures of normal (non H-deficient) PNe are scarce and generally indicate similar abundances than in the rims. The exception is the high nitrogen overabundance claimed for FLIERS; preliminary modeling on new observational data of the microstructures of NGC 7009 indicates that a moderate enrichment of nitrogen can be real.

1. Introduction

Planetary nebulae (PNe) arise from the evolution of the most abundant stars (1–8 $M_{\odot}$), and they are a key to understand the chemical evolution of galaxies and the production of crucial elements such as N and C. The gas in currently observed PNe originated only a few thousand years ago from the atmospheres of AGB stars but the information concerning its physical properties (density, temperature, kinematics, etc.), which are all very different now from when it belonged to the star, has been irretrievably lost. However, the PN gas does preserve the chemical information: a few elements change during the evolution of low and intermediate mass stars (notably He, C, N and s-elements), and we should be able to predict how they change, while most elements do not appreciably change (Ar, S, Ne, O, Cl, etc.), providing us with information on their pristine abundances at the time when the progenitors were formed. The chemical history of the stars is therefore attainable, although it is not at all easy to decipher. One of the great challenges in modern astrophysics is to link the abundances that we observe today in PNe with a stellar evolution theory that includes the (still poorly known) details of nucleosynthesis, convection plus dredge-up processes, and mass loss, all complicated functions of progenitor mass, metallicity, and time.

Chemical abundances are also a tool for investigating how and in what evolutionary phases the PN morphological features originate (the main shells, the halos, and the so -called microstructures), and this information is in turn a key to understanding how the PNe themselves were formed. PN global abundances, halo abundances, and the still poorly known chemical composition of the microstructures will be discussed here in Sections 2, 3, and 4, respectively. Each one sheds light on the chemical history of the stars and on the origin of the structures in PNe.

2. Abundances and Main Shell Morphology

Since the work of Manuel Peimbert and colleagues in the seventies, it has been noticed that Type I PNe (defined as having high He and N abundances) often show bipolar morphology, and quests began for correlations between chemical abundances and PN morphology in the hope that they would provide i) clues to the origin of the morphology [1] and ii) information on the masses and ages of the progenitor stars. Pottasch (2000) in his review at the last APN conference, presented accurate abundances for 16 PNe, concluding that 'no simple relationship between morphology and composition exists.' Two recent papers by Manchado (2003) and Phillips (2003) analyze abundances of some 75–85 PNe taken from the literature (Phillips 2003) or recalculated from published spectral data using the "constant $T_{\rm e}$, $n_{\rm e}$" method and IRAF routines (Manchado 2003). Table 1 shows a summary of their results for He and the N/O ratio; data from Perinotto & Corradi (1998) for a sample of 15 bipolar PNe have also been included for comparison. Note that values after the $\pm$ sign are not errors in quoted abundances but are instead 1-σ dispersions of the sample (Phillips 2003 and Perinotto & Corradi 1998) and the 50% percentile (Manchado 2003). Typical uncertainties in individual measures are difficult to estimate but probably range from 5 to 15% for He and 30–300% for metals. The table shows a small marginal increase in He from round, to elliptical, to bipolar PNe, plus a very high increase in N/O for bipolar PNe. This reinforces the current view that considers round PNe as originating from long-lived low-mass stars, whereas bipolar PNe would come from more massive and younger progenitors. Elliptical PNe would span a wide range of masses and ages (Phillips 2003). Given the uncertainties mentioned above, it is difficult to extract further trustworthy information from such statistical correlations, and one should move toward a better nebular analysis of individual objects. UV, optical, and IR (ISO) data now allow 30% accuracy in abundances for C, N, O, Ne, S, and Ar, their ionization correction factors (ICF) being around unity (Pottasch 2000). Helium abundance accuracy is around 5%. Abundances have recently been calculated by different authors in this way for some 20 PNe, although targets are necessarily biased towards bright and nearby (0.5 to 2.5 kpc) objects.

A brief summary of the best-observed PNe is given in below, together with a comment on the global results for each morphological class. *Round PNe*: A39 (Jacoby et al. 2001), IC 2165 and NGC 5882 (Pottasch et al. 2003a). These PNe

[1] Note that we do not have yet a theory that explains if and why a, say, 1 $M_\odot$ star will form a bipolar, an elliptical, or a round PN.

Table 1. PNe abundances and morphological classes.

	Round	Elliptical	Bipolar	References
He/H	0.102±0.010	0.121±0.015	0.136±0.010	(a)
	0.107±0.010	0.115±0.014	0.132±0.015	(b)
	–	–	0.150±0.040	(c)
N/O	0.27±0.08	0.31±0.15	1.30±0.50	(a)
	0.22±0.06	0.33±0.16	0.90±0.21	(b)
	–	–	1.39±1.02	(c)

(a) Manchado (2003); (b) Phillips (2003); (c) Perinotto & Corradi (1998)

show less processing (He, N, and C) than more structured PNe and would come from low mass progenitors having metallicities from solar to 2–3 times solar. *Elliptical PNe*: NGC 7662, NGC 6741 (Pottasch et al. 2001), NGC 40, NGC 6153 (Pottasch et al. 2003b), and NGC 6543 (Hyung et al. 2000; Bernard-Salas et al. 2003). Some of these PNe show very little processing (NGC 7662) and others much more (NGC 6543). Again they should come from low mass progenitors with different metallicities, from half solar to 2–3 times solar. *Bipolar PNe*: NGC 6302, NGC 6445, NGC 6537, He2-111 (Pottasch et al. 2000), NGC 7027 (Bernard-Salas et al. 2001) and Hb-5 (Pottasch et al. 2003c). The progenitors are all of intermediate mass, 3-4 $M_{\odot}$ (NGC 7027, NGC 6445, and possibly Hb-5) to larger than 4 $\mathrm{M}_{\odot}$ (NGC 6302, NGC 6537, and He2-111). These PNe show large He and N processing.

With accurately determined abundances, a sensible test for models is possible. Marigo et al. (2003) compare data for ten PNe with surface stellar abundances from evolutionary models for the thermal pulse–AGB phase. Two classes of PNe are found according to their He abundance; those with He/H ≥ 0.15 show much less C and O than PNe of lower He/H, and models with different initial conditions are required. The latter group of PNe would originate from AGB stars of low and intermediate mass (0.9–4 $M_{\odot}$) with initial solar metallicity, and their abundances of He, N and C are well explained with first, possibly second, and third dredge-up processes. The group with He/H $\geq$ 0.15 would instead come from intermediate mass stars (4–5 $M_{\odot}$) of subsolar (LMC-like) metallicity. Their abundances (including the low O values) can be explained with both the third dredge-up and the HBB, but a strong third dredge-up has to be assumed that very efficiently produces He, but is peculiar in not producing much C.

In summary, Marigo et al. (2003) are able to explain the observed PN abundances but find an important "age-metallicity" problem: if PNe with He/H $\geq$ 0.15 come from high mass progenitors then these should have formed relatively recently, and this seems to be in conflict with their having a low (LMC) metallicity (the Galaxy is expected to increase secularly in metallicity). Either some physical problem has not been properly taken into account or there are impor-

tant chemical peculiarities in the Galaxy. Alternatively, abundances in high He/H PNe (all of them being bipolar) could be affected by binarity.

3. Halos

By comparing the abundances in the halos and the main shells of PNe one aims to get information concerning when and through what processes the halos were formed. Guerrero & Manchado (1999) found similar abundances in the halos and the rim of six PNe, whereas in two nebulae, NGC 6720 and NGC 5882, the N^+/O^+ ratio in the halo was around half than at the rim. According to those authors, the mild (or null) enrichment at the rims is a sign of a small (or null) effect of the third dredge-up in the progenitors. However, the T_e could not be measured for the halos, and a deeper study is desirable. On the theoretical side, Villaver et al. (2002, 2003) find that the ISM can contaminate genuine halos adding up to 70% (for a 1 $M_\odot$ progenitor) to the halo mass during the evolution of the nebula. Furthermore, if the AGB progenitor moves with a velocity of 20 km s^{-1} with respect to the ISM, most (again up to 70%) of the mass ejected could be lost through ram-pressure stripping caused by the interaction. Both effects ought to change the actual halo abundances substantially, thereby complicating interpretations, although no detailed predictions are available yet.

4. Microstructures

4.1. Cometary Knots

Their chemistry is not known. O'Dell et al. (2000) suggest that [OIII]/Hα and [NII]/Hα are larger in a couple of inner knots than in the outer ones in NGC 7293. This could be caused by O and N being more abundant in the inner regions or (perhaps more plausibly) having a higher T_e. More work is needed here.

4.2. Knots in H-Deficient PNe

A78 and A30 are the best examples of PNe with large abundance variations. Medina & Peña (2000) confirm the extremely high He abundances in the inner knots of A78 but find normal O, N, and Ne, which suggests that the gas was ejected from zones at the central star after nucleosynthesis took place. They also discovered a high velocity outer knot, colliding with the shell, where H is underabundant. This feature deserves a more complete chemical analysis.

Ercolano et al. (2003) modeled the inner knot (J3) of A30, finding that the optical recombination line (ORL) emission came from a dense ($n_{\rm He} = 10^4$ cm^{-3}) and cold ($T_e = 10^3$ K) core, whereas the collisionally excited line (CEL) emission would originate at a less dense ($n_{\rm He}$= 1700 cm^{-3}) but very hot (T_e= 16 000 K) envelope. The long-standing ORL/CEL abundance discrepancy might find an explanation if density and chemical inhomogeneities such as those of J3 were ubiquitous in ionized regions.

4.3. Knots in Normal PNe

An exciting discovery in NGC 5315 (a normal PN with an H-deficient central star) has been reported by Pottasch et al. (2002): the presence of two He-rich

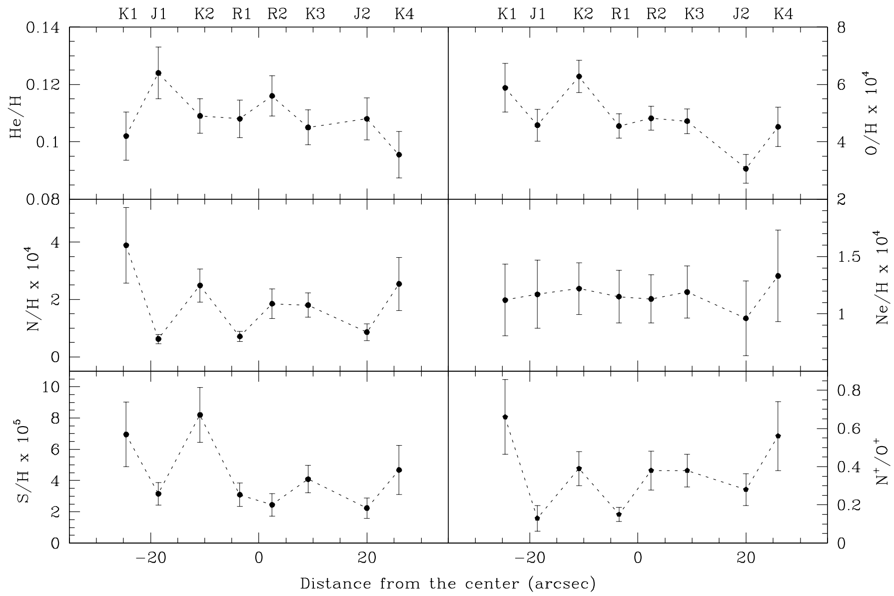

Figure 1. Abundance profiles of NGC 7009 for He, O, N, Ne, S, and the N^+/O^+ ratio. The positions of the eight selected features are marked in the upper part of the plot. After Gonçalves at al. (2003).

microstructures (of size ∼0.6 arcsec) located in a bipolar fashion in the inner nebula. Its origin is not known and further work, including measurement of their abundances and kinematics, is required. Perinotto et al. (2003) analyze the physico–chemical conditions of the FLIERS (and their antagonists, the so called SLOWERS) in NGC 7662. The previously reported N overabundance of the FLIERS (Balick et al. 1994) is not confirmed, although the analysis is limited by uncertainties concerning the role of charge-exchange reactions in the derived abundances. More on this issue in the following section.

4.4. Microstructures of NGC 7009

Czysak & Aller (1979) discovered a strong nitrogen overabundance in the outer knots (the ansae) of NGC 7009, a result confirmed by Balick et al. (1994), who found five times more N in the western ansa than at the rim; this was interpreted as the product of the recent high velocity ejection of N-rich material from the central star. Similar overabundances were also found in the low ionization knots of two other nebulae, NGC 6543 and NGC 6826, resulting in N/O values up to six times larger than in the cores. Ten years later, the origin of this N-richness and of the FLIERS themselves remains a mystery (Gonçalves et al. 2001).

Gonçalves et al. (2003) studied the rim, jets, and knots of NGC 7009 with deep optical spectra and a detailed analysis of the errors affecting both the physical parameters and the abundances. They find a moderate overabundance, of a factor of two, in N/H and N/O in the outer knots K1 and K4 (Figure 1. For an image of the nebula and its microstructures see Figure 2 in Gonçalves's contribution in this volume). Obviously, this cast doubts on previous results

and on the process itself for calculating abundances via the ICFs, but, if *any* overabundance prove to be real, then the problem of its origin would persist.

So is the nitrogen overabundance in FLIERS real or a conspiracy? Alexander & Balick (1997) and Gruenwald & Viegas (1998) showed that long-slit data may give spurious overabundances of N and other elements in the outer regions, and knots, of model PNe. The main culprit is the different charge-exchange reaction rates of N and O, affecting the N^+/O^+ ratio mainly in the external low-ionization regions of the nebulae. As N^+/O^+ is usually assumed to be a good ICF for nitrogen, any extra quenching of O^+ with respect to N^+ caused by the charge-exchange reactions will translate into an N overabundance via the overestimated ICF. However, it is not clear how close simple geometries and plane–parallel models like CLOUDY approach complex objects such as the microstructures of NGC 7009, nor why other elements such as Ne, Ar, S, etc., also expected to show spurious overabundances, do not do so. This unresolved issue continues to prevent a robust interpretation of observed abundances in microstructures (Perinotto et al. 2003).

One approach would be to try to work with ICFs of order unity, i.e., observing the whole range of lines of the different ions, so avoiding the use of, in particular, the O^+ ionic abundance in the total N abundance. However, this implies getting adequate UV and IR data for the microstructures, which is not an easy task today. The alternative is to tailor-model individual cases with an appropriate 3D photoionization code that allows complex geometries and density distributions, and possible abundance variations. We have made a preliminary test of the role of charge-exchange reactions on measured abundances in NGC 7009 using MOCASSIN (Ercolano et al. 2003) with the following input parameters: i) a central star of $T_{\rm eff} = 82\,000$ K and luminosity 2500 $L_\odot$ at an assumed distance of 1 kpc; ii) three constant density components: R1, modeled as an ellipsoidal shell with density 4910 cm^{-3}; J1, as a cylindrical jet with 1155 cm^{-3}; and K1, as a disk-shaped knot perpendicular to J1 with 2300 cm^{-3}; iii) temperatures are self-consistently derived in each region from modeling, and iv) abundances are those empirically derived for each component, except for K1 where N/H = 1.15 10^{-4} is assumed (giving best fit for observed N lines in K1). The effect on the N/O abundance ratio of including (*on* model) or excluding (*off* model) all charge-exchange reactions in the calculations is $[N^+/O^+]_{\rm off}/[N^+/O^+]_{\rm on}$ = 1.13, 1.16, and 1.18 for R1, J1, and K1, respectively. It appears, therefore, that charge-exchange reactions are responsible for only a modest overestimation of N/O, of order 20% in the external knots. Either the nitrogen enrichment at the knots is real, or another factor is affecting the results. As discussed by Gonçalves et al. (2003), neither collisional quenching of the [OII] lines nor strong shocks (enhancing the [NII] lines) seems at work at K1 and K4, and one is forced to accept that N/O can be really twice as large in these knots than at the rim in NGC 7009. The issue is currently being investigated with a more detailed model that includes the whole nebula.

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